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Leachate Generation from Biomass Operations: a subproject of the Woody Biomass Innovative Project

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ABSTRACT

As part of the Woody Biomass Innovative Project, which proposes to assess future bioenergy potential for British Columbia, a study was conducted to assess wood biomass leachate effect on water quality. The study aims to provide guidance for policy development related to biomass operations and their leachates. To that end, we examined the impacts of roadside chipping with respect to the amount of leachate generated, aquatic toxicity, and connectivity between post-biomass processing wood residue piles and streams in central interior British Columbia. Best practice considerations specific to on-site processing, road networks, soils, and riparian zones are provided based on field assessments of biomass sites, consultation with biomass processors, and a review of management practices in other jurisdictions.

ACKNOWLEDGEMENTS

The authors would like to thank Phillip Krauskopf for his work on the rainfall simulation and static tests, and Eiji Matsuzaki, Chris Bailey, and Andrea Eastham for their efforts in conducting the biomass processing assessments. Furthermore, we would like to thank Richard Kabzems, Norm Bilodeau, and Shannon Carson for reviewing an earlier version of this report and providing helpful comments.

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1 INTRODUCTION

The use of wood for energy production is increasing globally because it is renewable, is broadly available, and can be used across a range of technologies from direct incineration to production of bio-oil (FAO 2008). In British Columbia, wood use for energy production is gaining popularity due to a suite of factors, including the recognition of society's increasing energy demand, concern about fossil fuel use and climate change, availability of mill wood residues, and presence of vast stands of dead pine trees that are no longer suitable for sawlog production due to the mountain pine beetle epidemic (Stennes and McBeath 2006; Beauchemin and Tampier 2008). Wood biomass is an attractive source of alternative energy, but to be considered viable, it must be environmentally acceptable (McDaniels 1982; Janowik and Webster 2010; McKone et al. 2011; Lamers et al. 2013).

To ensure the environmental sustainability of the wood biomass industry in British Columbia, it is necessary to assess the influence of biomass development on resource values, including water. This report outlines an investigation on the impacts of biomass operations on water quality by determining the potential for leachate generation and aquatic toxicity from wood chips produced during biomass operations and the connectivity between biomass processing sites and aquatic areas. The goal of the investigation was to identify water resource impacts associated with roadside processing and to provide best management practices.

Wood leachate studies have traditionally focussed on log storage yards because they produce large quantities of leachate due to the high volume of wood stored and the frequent watering of logs to prevent them from cracking or succumbing to biological attack (Orban et al. 2002). This biomass study is based on much smaller quantities of wood from typical roadside and cutblock chipping operations rather than whole logs. These are important differences because biomass development activities are a non-point source impact rather than a point source, such as log yards. In addition, leachate generation may differ between wood chips and whole logs given that wood chips have a greater surface area for water to act upon. Despite these differences, log yard leachate research findings are the foundation from which to consider leachate generation from biomass operations.

Previous log yard studies have shown that the quantity of leachate generated increases with the amount of water that has come into contact with the wood (Hedmark and Scholz 2008). Although leachate chemistry can vary among tree species and over time, leachate generally has both high organic matter content and chemical oxygen demand (COD) (Hedmark and Scholz 2008). Wood leachate can degrade water quality and is toxic to aquatic life (Taylor and Carmichael 2003; Libralato et al. 2007). The aquatic response to leachate is associated with increased COD, phenols, organic compounds, or resin acids (Hedmark and Scholz 2008).

Leachate generation may occur at biomass processing sites prior to processing when harvested logs are stacked roadside or on the harvested land for periods that may extend from weeks to months after harvesting (Taylor and Carmichael 2003). During wood chipping operations, chip piles can be created by spillage, or during the regular cleaning of grinding equipment, or when chip piles are stored on the cutblock pending mill needs and market condi-

tions. Unless these piles are spread or removed, they will contribute leachate to local soils and to runoff (Kabzems et al. 2011). The latter is particularly important to aquatic environments because roadside processing, which is most operationally efficient for transport, can increase the probability of leachate reaching ditches and subsequently being delivered to streams.

The objectives of this project were to:

1. assesses the effect of a variety of sub-boreal tree species used for biomass energy production on leachate generation potential and aquatic toxicity;
2. assess connectivity between log chipping locations and receiving streams; and
3. identify best management practices related to drainage issues during biomass operations.

2 METHODS

To address the project objectives, two investigations were conducted. The first study involved the assessment of leachate generated by various tree species used in biomass operations. The second involved an inventory and assessment of biomass operations in the Prince George Forest District (Figure 1) to identify connectivity between biomass processing sites and proximal streams.

FIGURE 1 *Location of the Prince George Forest District, British Columbia.*

2.1 Leachate Generation and Toxicity Studies

Short-term leachate generation potential was assessed by exposing wood chips to 28-day static laboratory tests and 1-hr rainfall simulations; long-term leachate generation was assessed by sampling chip piles from field operations locations over a 548-day period.

2.1.1 Wood sample preparation Two wood chip sampling methods were used depending on whether the wood chips were used for operational field trials or laboratory trials. Two operational field trial locations (Muldowan 18 and Muldowan 22) were established in salvage blocks in co-operation with a local biomass operator. Lodgepole pine (*Pinus contorta* var. *latifolia* [Pli]) and spruce (*Picea engelmanii* [Sx]) logs were randomly chosen from decked logs to reflect the 90% Pli:10% Sx ratio that existed at the block level. Trees were chipped into two (322 L each) uncovered plastic horse watering trough containers with bottom drain plugs. Due to mechanical issues, two different wood chip screen sizes were used during grinding: a 10-cm screen was used at the Muldowan 18 station, and a 5-cm screen was used at the Muldowan 22 station.

Wood chipped for static and rainfall simulation laboratory trials was gathered from debris piles in two separate mountain pine beetle salvage blocks 20 km north of Prince George. Tree stems were removed from the pile, and bark and needles were used to identify the stems as lodgepole pine, hybrid spruce, or black spruce (*Picea mariana*). Aspen (*Populus tremuloides*) was identified by bark alone. These stems were chipped using an unscreened Vermeer 1000 chipper.

2.1.2 Leachate generation Operational samples were left in uncovered 322-L containers that sat above ground in the field and were exposed to natural weather conditions over a 548-day period from the winter of 2010 until the fall of 2012. Samples were collected following spring melt and after late summer and fall rains. At each sample collection date, the entire volume of leachate in the containers was drained to ensure that the next sample collected would contain newly generated leachate.

Leachate was generated in the laboratory using de-ionized water in a static exposure and a rainfall simulation. The static exposure consisted of placing 2 kg of wood chips in a 1-cm opening polypropylene mesh bag in 18 L of water for 28 days at room temperature and ambient light. The quantity of chips and water used followed the 9:1 ratio of water to wood recommended by Taylor et al. (1996). Static exposure tests were completed using duplicate samples of separately chipped lodgepole pine, hybrid spruce, black spruce, aspen, and mixed pine and spruce chips from the operational sites. Water samples were drawn weekly for chemistry and aquatic toxicity analysis.

A portable rainfall simulator was used to generate rainfall leachate samples (Clarke and Walsh 2007). The simulator generated a heavy rainfall event of approximately 100 mm/hr. Dry chips were exposed to the rain event, after which they were soaked for 12 hr, and then were exposed to another rain event. Both treatments were used to identify differences between dry and saturated wood chips.

2.1.3 Chemistry, toxicity, and statistical analysis Operational site leachate samples were collected in 20-L plastic containers that had lids and were washed with phosphate-free soap. In the laboratory, subsamples were collect-

ed from the containers by dipping sterilized 120-ml amber glass bottles (for phenol analysis) or acid-washed plastic bottles (for all other analyses) into the container after mixing the solution. The bottles were inserted in an inverted position until mid-depth and then were turned right side up to collect the sample. Static test leachate samples were collected in the same manner as the operational samples because wood chip samples were placed in 20-L buckets. Simulated rainfall samples were collected from a receiving bin below the wood chip sample that was exposed to rainfall (Figure 2).

Once collected, all samples were stored at 4°C until they were shipped with ice to commercial laboratories for analyses using standard techniques and detectable thresholds, as identified (Table 1). Quality assurance and control protocols included the submission of blank samples, duplicates, and spiked samples. Microtox™ analysis used the luminescent bacterium *Vibrio fischeri*, and processing followed standard techniques at dilutions of 0%, 10.2%, 20.4%, 40.9%, and 81.8% (Environment Canada 1992). For this study, Microtox™ tests were used to determine the effective concentration of leachate that reduced the bacteria population by 50% within 15 minutes. Toxicity is inferred by the concentration required to cause population reduction: the lower leachate sample concentration required, the higher its toxicity. Previous studies identified the organic component of wood leachate as the primary toxicity agent (e.g., Taylor and Carmichael 2003); consequently, Microtox™ test findings are considered to be representative of response by more complex organisms, such as rainbow trout (Qureshi et al. 1982; Munkittrick et al. 1991).

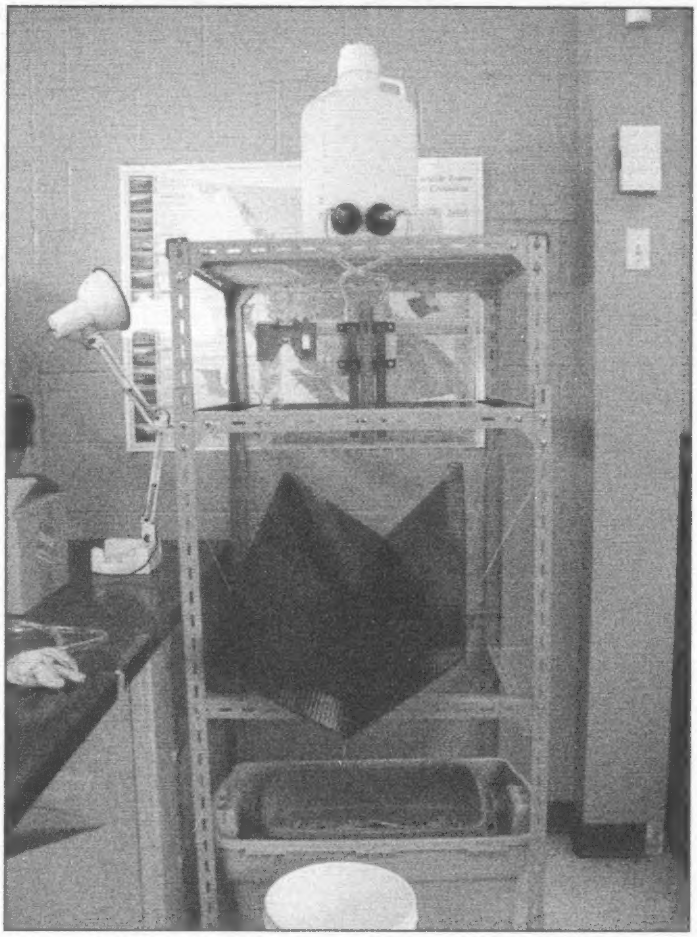

FIGURE 2 *Portable rainfall simulator (after Clarke and Walsh 2007) showing the nested wood chip and leachate sample container on the floor, the plumbed water carboy containing de-ionized water, and the Plexiglas® header tank and raindrop downspouts. The dark plastic sheet was used to intercept rainfall during pre-exposure rainfall calibration.*

TABLE 1 *Chemistry analytical techniques and detection limits*

Parameter	Analytical technique	Detection limit
pH	Electrometric method (SM-4500H+B)	
True colour	Visual comparison method (SM-2120B)	100 colour units (TCU)
Total organic carbon	Persulfate-ultraviolet or heated-persulfate oxidation method (SM 5310 C)	5.0 mg/L
Chemical oxygen demand	Closed reflux, colorimeter (SM-5220D)	20 mg/L
Ammonium	Automated phenate method (SM-4500NH3G)	0.005 mg/L
Resin acids	Extraction and gas chromatography (STL SOP-00152)	
Phenols	Direct photometric method (SM 5530)	0.01 mg/L
Microtox™	Biological test method: toxicity test luminescent bacteria, 1/RM/24: Environment Canada	

All statistical analyses were completed using Systat 11™ (2009), and figures were constructed using SigmaPlot 11™ (2009). To identify temporal and sample differences, repeated measures ANOVA was conducted for each type of sample using duplicate sample data for each sample period (Sokal and Rohlf 1995).

2.2 Inventory and Assessment of Biomass Sites

2.2.1 Field site selection Candidate sites were blocks that were harvested within the last 2 years and that had biomass utilization in the harvesting profile. A list of 30 candidate sites was obtained from the Prince George Forest District office. Each site was visited for field assessment during the late summer and fall of 2012, but only 17 of the sites was acceptable for inspection. Excluded sites were either unharvested or there was no biomass processing on-site, as identified by the absence of waste residue piles.

Prior to field visitation, details about candidate blocks were retrieved from available databases to identify the block area and road layout and determine if streams that provided fish habitat or potable water supply were in the block or along its boundary. Once acceptable sites were located in the field, the block roads were traversed and geo-referenced. Processing areas were then counted, and a site inspection was completed at all or a representative number of processing locations. The site inspection assessed the entire processing area and required completion of a standardized field form to ensure that soil and hydrology questions were answered consistently for each site (Appendix 1).

This inventory was purposefully broad because there were no pre-existing data or methods for biomass processing effects on hydrology and soils in the Prince George Forest District. Accordingly, data are presented in a summary form rather than as a comparison between sites or management practices.

2.2.2 Soil disturbance assessment and texture Dispersed soil disturbance was assessed within the biomass processing area using the classification criteria outlined in the Forest and Range Evaluation Program *Protocol for Soil*

Resource Stewardship Monitoring: Cutblock Level (Curran et al. 2009). These criteria are the same as those defined in the *Soil Conservation Surveys Guidebook* (British Columbia Ministry of Forests 2001). Soil texture at each site was determined by Stéphane Dubé following the procedure for hand texturing (British Columbia Ministry of Forests 2001).

3 RESULTS AND DISCUSSION

3.1 Leachate Generation and Toxicity Assessment

3.1.1 Field operational samples Differences between parameters and sites were observed over the 548-day exposure period (Figure 3). The COD samples drawn from larger chips at Muldowan 18 were 10–40% lower than those drawn from smaller chips at Muldowan 22 ($F_{1,2}$=34.2, p=0.03). There was also a substantial decline in COD over time at both sites: the final recorded values were approximately 25% that of the initial reading ($F_{4,8}$= 57.2, p<0.001).

The total organic carbon (TOC) samples showed a similar trend. Muldowan 18 had significantly lower concentrations than did Muldowan 22 ($F_{1,2}$=21.6, p=0.04) and a decrease in concentration over the sample period ($F_{3,6}$ =22.1, p=0.001): the final samples were approximately 25% that of the initial samples. These results support the suggestion that particle size influences leachate characteristics, and that small chips should be avoided due to larger exposed wood surface area (Samis et al. 1999).

There was no significant difference in true colour between samples or sample periods. However, there appeared to be a temporal trend; that is, decreased true colour that followed changes in pH as wood chips aged over time (e.g., Tao et al. 2005).

Phenols spiked in the second sample at both sites and decreased over the remaining sample period, which led to a significant difference between sample periods ($F_{3,6}$=39.4, p=0.001). Lignin-derived phenols, along with carbohydrates, account for most wood decomposition, especially early in the exposure period for softwood (Jirjis and Theander 1990).

Although there was a difference in ammonia concentrations between samples on the first sample date, there was no significant difference between sites over the entire sampling program. There was a significant difference across weeks as ammonia concentrations declined ($F_{3,6}$ =15.2, p=0.03). As shown in Figure 3, less than 2 years after exposure, ammonia runoff was close to acceptable levels to protect aquatic life (<0.2 mg/L for manure leachate) (FAO 2014).

Leachate pH conditions were similar at the two sites during the first samples but were more variable over the final two samples, which led to an overall significant difference between sites ($F_{1,2}$=729.1, p=0.01) and sample periods ($F_{3,6}$=281.4, p<0.001). The pH of the leachate was acidic, in large part due to the loss of sugars from the chips (Hunt and Kuechler 1971), particularly during the first year (pH<4.5, Figure 3). Toxicity from wood leachate is attributed in part to low pH and its effects on various runoff parameters, such as COD (Tao et al. 2005, 2007).

Organic compounds decreased over the exposure period but remained quite high (COD >1000 mg/L, TOC >500 mg/L, and colour >500 TCU). In log yards, degradation of organic matter is a main contributor to oxygen con-

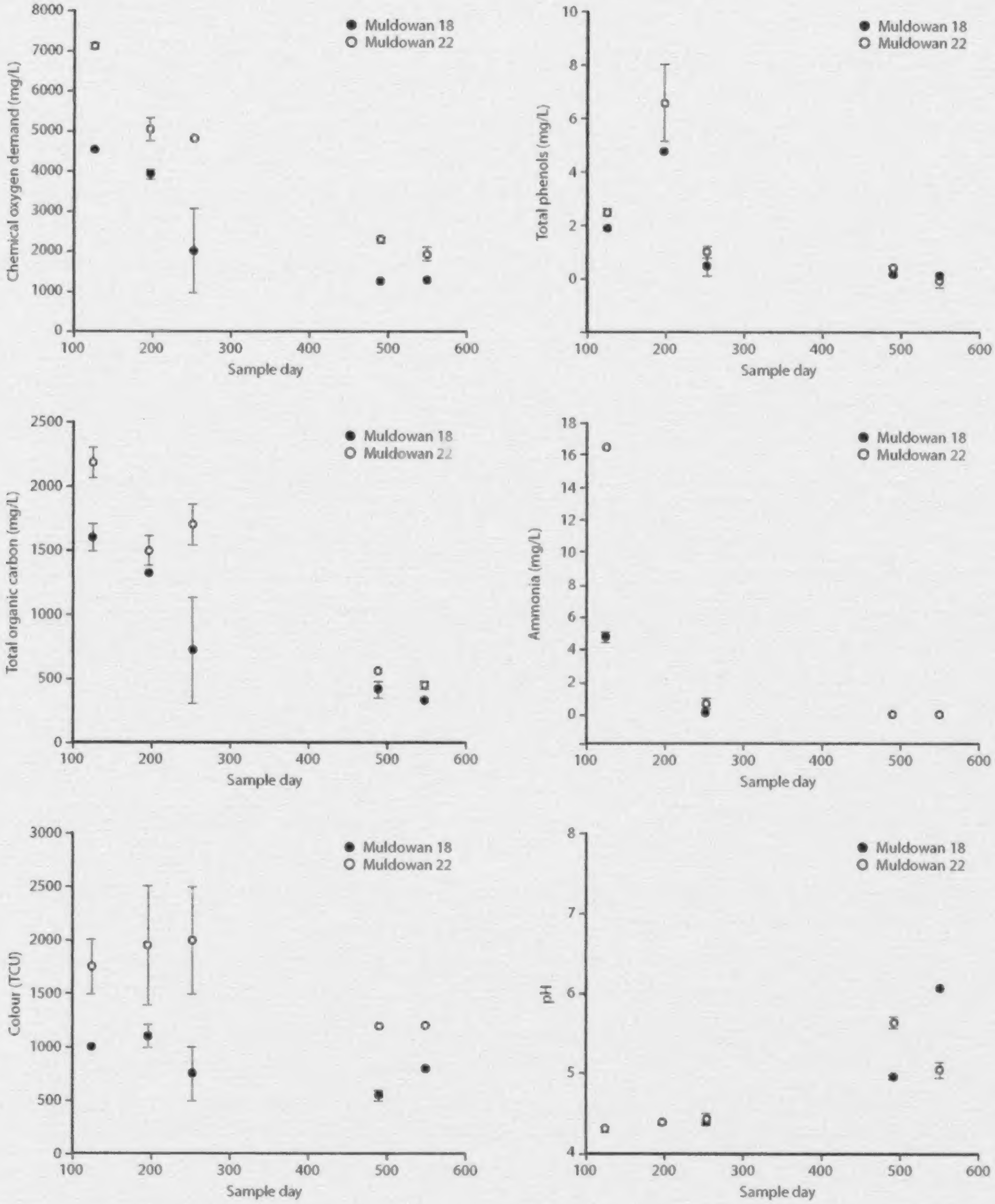

FIGURE 3 *Operational site leachate parameters over the 548-day exposure period. Bars represent standard errors.*

sumption (Hedmark and Scholz 2008). Accordingly, remnant chip piles from spillage or equipment cleaning have the potential to be a long-term source of dissolved organics to receiving streams; high concentrations of organic compounds in streams may lower dissolved oxygen levels. TOC of runoff from wood chip piles exceeded what is typically found in log yard runoff (Jonsson

et al. 2006) and was higher than that reported in aspen wood leachate field studies (Taylor and Carmichael 2003); our field samples contained very little aspen. High COD (Hao et al. 1996) or COD in combination with other chemical concentrations (Gutierrez et al. 2002) may be correlated with toxicity.

Due to the availability of only one toxicity sample for Muldowan 18 during the final two sample dates, no statistical analysis was conducted. Some variability between samples was noticeable, but there was no obvious pattern. Although statistical comparison was not possible, it is noteworthy that all samples collected over the 548-day exposure produced a toxic response in *Vibrio fischeri*, as noted by EC_{50}, within the 15-minute test period, but the Muldowan 22 sample was less toxic, as noted by the higher concentration required (Figure 4). Accordingly, it is reasonable to suggest that residual chip piles can produce toxic leachate for close to 2 years following biomass operations, if not longer. Similarly, Taylor and Carmichael (2003) noted that an 18-m^3 aspen log pile produced toxic leachate after 2 years, and only 10% of leachable material had been removed over the 2-year period. Our findings were consistent with identifying a broad potential for leachate generation where wood chip or log piles exist, although our piles consisted of chips not logs and coniferous not deciduous chips, and were considerably smaller at approximately 0.33 m^3 compared to other studies (e.g., Hedmark and Scholz 2008).

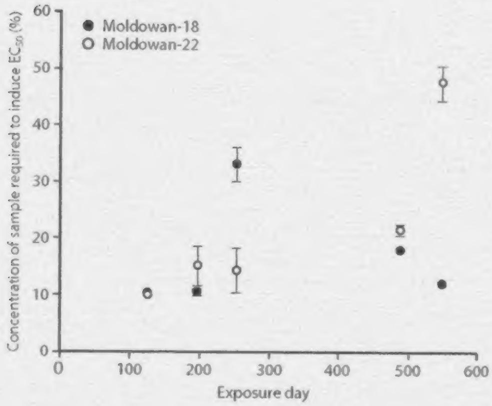

FIGURE 4 *Microtox™ findings for operational samples over the 548-day period. Bars represent standard errors. The final two samples for Muldowan 18 were based on a single measurement due to sample tampering.*

3.1.2 Static samples Coniferous leachate chemistry was relatively constant over the 28-day exposure period (Figure 5). Aspen leachate was significantly higher in all measured parameters except pH, which was significantly lower than the coniferous leachate (Figure 5, Table 2). Aspen phenols, pH, and ammonium decreased over the 28-day sampling period. All leachate samples showed a consistently high toxicity response over the 28-day sampling period as each was toxic at concentrations less than 10% by volume (Figure 6).

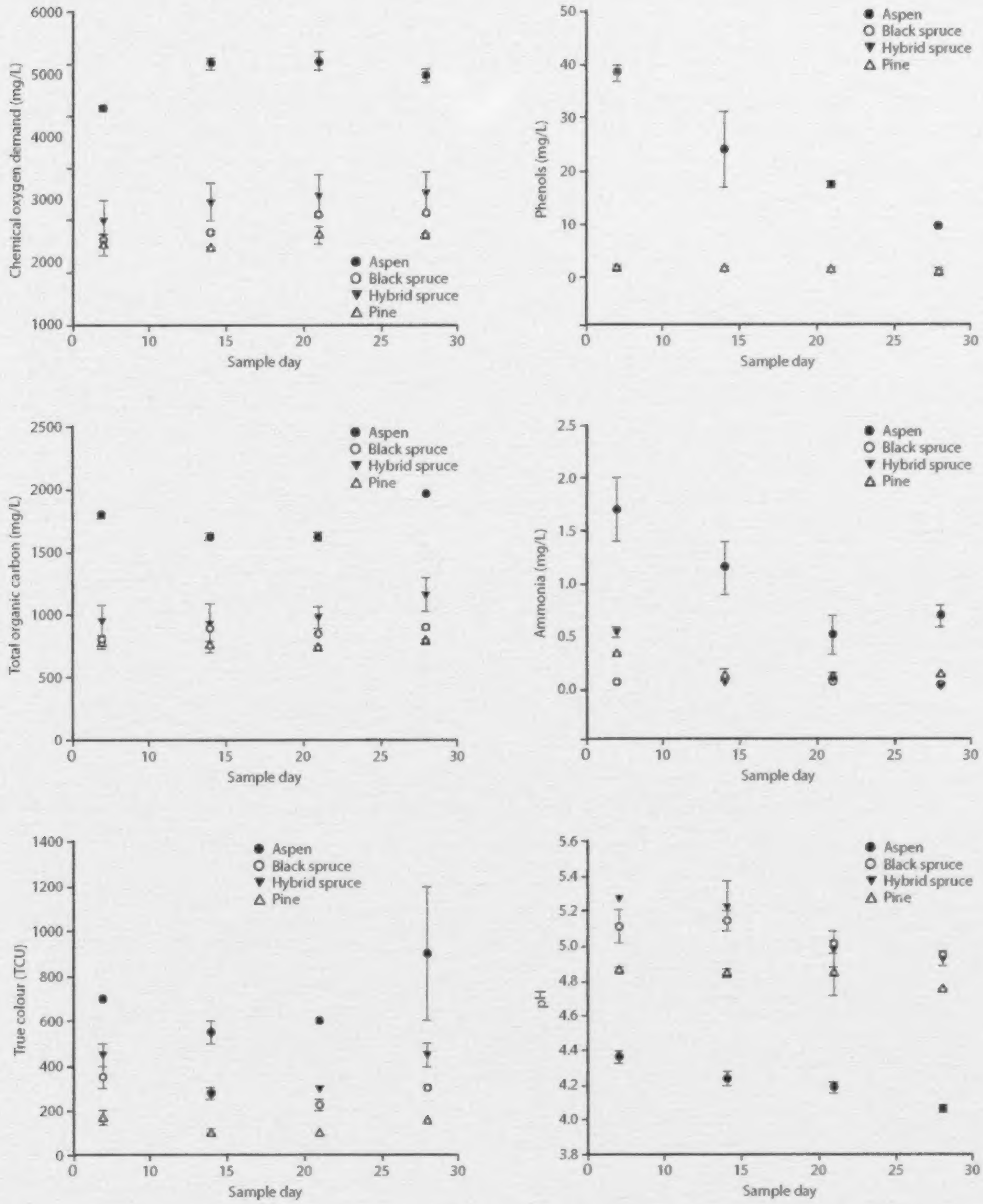

FIGURE 5 *Static test leachate chemistry for each tree type over the 28-day exposure period. Bars represent standard errors.*

TABLE 2 *Repeated measures ANOVA summary statistics for six chemistry parameters used to identify differences between tree species across the 28-day sample period*

Parameter	Between trees	Within subjects
Total organic carbon (TOC)	$F_{3,4}$=51.99, p=0.001	TOC $F_{3,12}$=40.64, p<0.001 TOC • Tree $F_{9,12}$=10.98, p<0.001
Chemical oxygen demand (COD)	$F_{3,4}$=50.08, p=0.001	COD $F_{3,12}$=25.05, p<0.001 COD • Tree $F_{9,12}$=3.99, p=0.048
True colour	$F_{3,4}$=89.35, p<0.001	Colour $F_{3,12}$=27.82, p<0.001 Colour • Tree $F_{9,12}$=2.93, p=0.047
Phenol	$F_{3,3}$=196.70, p=0.001	Phenol $F_{3,9}$=6.45, p=0.013 Phenol • Tree $F_{9,12}$=6.87, p<0.004
Ammonia	$F_{3,4}$=395.9, p<0.001	Ammonia $F_{3,12}$=17.70, p<0.001 Ammonia • Tree $F_{9,12}$=5.62, p=0.004
pH	$F_{3,4}$=74.3, p=0.001	pH $F_{3,12}$=18.42, p<0.001 pH • Tree $F_{9,12}$=2.10, p=0.12

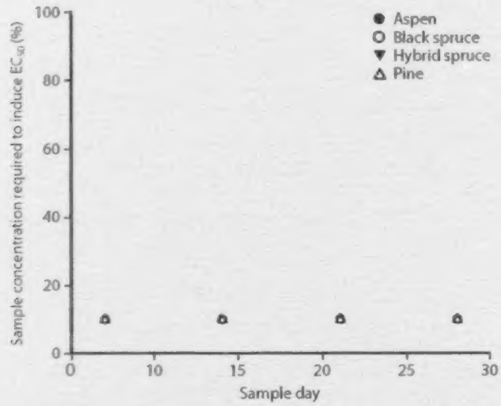

FIGURE 6 *Microtox™ EC_{50} for static test samples. Bars represent standard errors (n=2).*

3.1.3 Rainfall simulations Wood chip moisture levels increased over the 1-hr rainfall event by approximately 19–28% by volume (Table 3). Moisture level increase for aspen was less than that for the coniferous species. Pine showed the highest increase in moisture content by species, and all the operational samples exhibited the highest starting moisture content in the saturated sample run. Compared to their starting condition, wood chips generally lost moisture over the course of the saturated sample run (Table 3).

Saturated chip samples generally produced a leachate that had higher concentrations of measured chemical characteristics except for ammonia where data were variable and standard errors overlapped (Figure 7), but not all differences were statistically significant (Table 4). In the dry condition, wood chips produced leachate that was relatively similar across tree species, whereas in the saturated condition, aspen leachate generally had a higher

concentration of each parameter except pH, which was lower, and true colour, which was not measured.

TABLE 3 *Rainfall simulation wood chip moisture levels for dry and saturated runs, and moisture gained (standard error in brackets, n=2)*

Sample	Condition	Starting moisture (%)	Moisture gained (%)
Bobtail	Dry	0.0	18.5
Bobtail	Saturated	35.5 (0.4)	3.0
Muldowan 18	Dry	0.0	28.0
Muldowan 18	Saturated	36.6 (5.4)	-1.3
Muldowan 22	Dry	0.0	19.8
Muldowan 22	Saturated	37.1 (1.9)	0.1
Pine	Dry	0.0	27.2
Pine	Saturated	34.2 (3.7)	-2.4
Hybrid spruce	Dry	0.0	20.5
Hybrid spruce	Saturated	34.2 (0.7)	-2.9
Black spruce	Dry	0.0	22.3
Black spruce	Saturated	33.3 (2.6)	-1.0
Aspen	Dry	0.0	19.2
Aspen	Saturated	30.4 (1.5)	5.3

TABLE 4 *Repeated measures ANOVA summary statistics to identify differences between leachate generated by different tree species and saturated or dry antecedent wood chip condition. Asterisks identify reduced sample sizes due to the absence of measurement for saturated aspen samples.*

Parameter	Between trees	Within subjects
Total organic carbon	$F_{6,9}$=25.18, p<0.001	Condition $F_{1,9}$ = 400.44, p<0.001 Condition • Tree $F_{6,9}$ =25.0, p=0.001
Chemical oxygen demand	$F_{6,9}$ =19.71, p<0.001	Condition $F_{1,9}$=222.6, p<0.001 Condition • Tree $F_{6,9}$=12.03, p=0.001
True colour*	$F_{5,8}$=30.8, p<0.001	Condition $F_{1,8}$=436.41, p<0.001 Colour • Tree $F_{5,8}$=19.97, p<0.001
Phenol	$F_{6,9}$=37.43, p<0.001	Condition $F_{1,9}$=432.39, p<0.001 Condition • Tree $F_{6,9}$=60.01, p<0.001
Ammonia	$F_{6,9}$=2.97, p=0.07	Condition $F_{1,9}$=0.75, p=0.41 Condition • Tree $F_{6,9}$=2.96, p=0.07
pH*	$F_{5,8}$=1.87, p=0.21	Condition $F_{1,8}$=9.35, p=0.02 Condition • Tree $F_{5,8}$=2.94, p=0.09

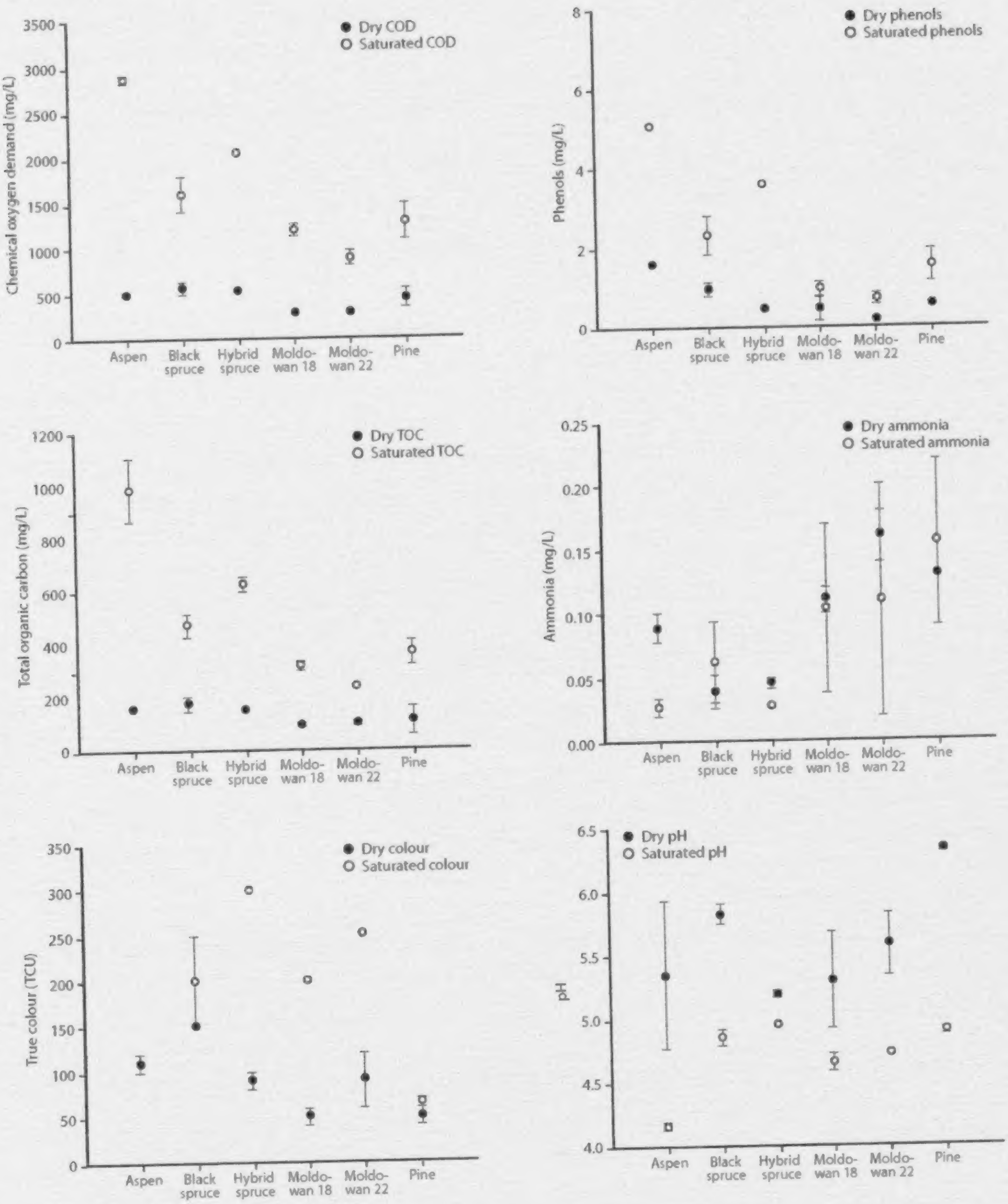

FIGURE 7 *Rainfall simulation leachate chemical conditions for dry and saturated wood chips. Bars represent standard errors.*

Coniferous leachate samples generated from saturated and dry wood chips were similar across species except for the low colour values in pine compared to spruce and mixed samples. Overall, leachate chemical composition generated from these 1-hr rainfall simulations was of the same magnitude as the operational samples and was quite similar to the 28-day static samples.

There was no significant difference in the toxicity of leachate between dry and saturated exposure within tree species (Figure 8) or among tree species. However, a higher concentration of the dry chip Muldowan 18 leachate samples was required to induce toxicity compared to the saturated sample and all other samples. This may be the result of differences in chip size because the Muldowan 18 chips were bigger (made using a 10-cm sieve) than those at Muldowan 22 (5-cm sieve).

Isopimaric acid and dehydrobietic acid (DHAA) responded similarly to the rainfall simulation conditions. DHAA concentrations were higher than isopimaric levels (Figures 9 and 10). Isopimaric acid concentrations differed significantly across tree species ($F_{5,6}$=12.2, p=0.004) and wood chip moisture conditions ($F_{1,6}$=5.7, p=0.03). Aspen did not have detectable levels of isopimaric acid. Coniferous samples were similar. The highest concentrations were found in the operational samples, particularly when leachate was generated from saturated chips. DHAA concentrations were also significantly different across tree species ($F_{5,6}$=47.5, p<0.001). Aspen and hybrid spruce exhibited the lowest concentrations; black spruce and pine exhibited the highest. The Muldowan 22 mixed sample had even higher concentrations. Although DHAA concentrations were often higher for dry chips than saturated across tree species, there was no significant difference ($F_{1,6}$=0.04, p=0.8). Isopimaric acid and DHAA levels were similar to concentrations that were previously identified as initiating a toxicity response (Peng and Roberts 2000; Lahdelma and Oikari 2005; Meriläinen et al. 2006) and likely influenced the toxicity response of rainfall samples.

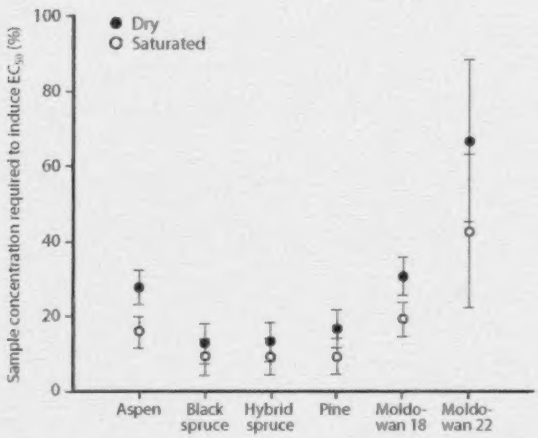

FIGURE 8 *Microtox™ EC_{50} mean values for rainfall simulation, including standard error bars.*

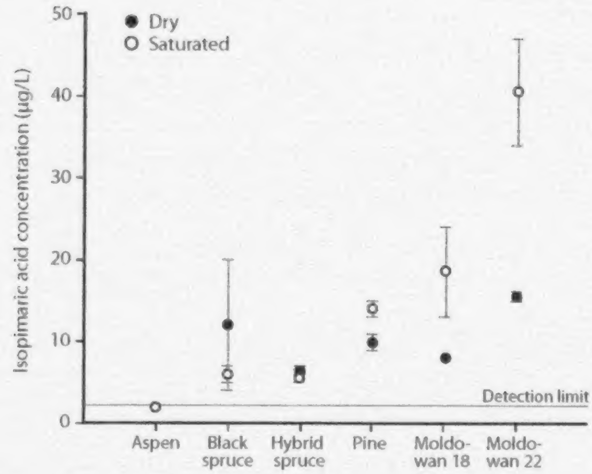

FIGURE 9 *Mean isopimaric acid concentrations by tree type and moisture conditions. Bars represent standard errors.*

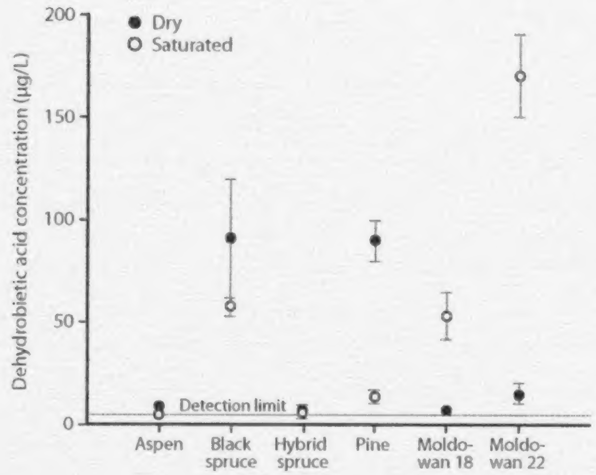

FIGURE 10 *Mean dehydrobietic acid (DHAA) concentrations for different tree types and wood chip moisture conditions. Bars represent standard errors.*

3.2 Inventory and Assessment of Biomass Sites

Harvested areas ranged from 16 to 526 ha and were in fish-bearing watersheds (Appendix 2). Stream channels were located on or near 12 of the 17 blocks inventoried. Nine of these streams were hydrologically connected to processing areas; therefore, runoff could reach the streams, particularly during storm events.

Soil compaction occurred in processing areas in 15 of the 17 blocks inventoried (88% of total, Figure 11); seven of those sites had severe or extreme levels of compaction. These results reflect cumulative disturbances in areas where timber harvesting and fibre recovery operations overlapped. Hand texturing (British Columbia Ministry of Forests 2001) indicated that soils were dominantly fine textured (e.g., silty loam) to 20 cm depth and therefore were susceptible to compaction. Compaction can increase surface runoff and erosion because the soil acts like pavement (Greacen and Sands 1980), which can lead to increased delivery of leachate to watercourses.

Waste residue and slash ground coverage ranged from <10 to 95% on all sites; six sites had >61% average slash coverage in operating areas (Figure 11). On all sites, residual wood waste was >10 cm deep and therefore could interfere with surface water and oxygen flow due to the high retention of excessive moisture. Under waterlogged conditions, leachate collects in the soil and may persist for a long time as pores fill (Kadlec 1999). This can lead to more leachate that is available for future runoff. Landscaping studies have shown that organic mulch layers that exceed 10–15 cm create poorly drained conditions. Wood waste application as soil amendment during reclamation can create poorly drained conditions (Venner et al. 2011).

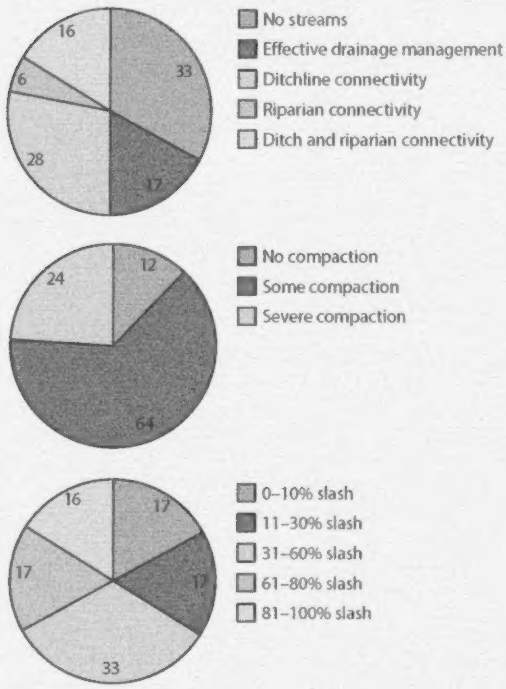

FIGURE 11 *Field inspection summary information for stream connectivity, soil disturbance, and slash coverage in the operating area. Pie slices show the percentage of sites in each category.*

Soil condition and connectivity with aquatic sites in the processing area were influenced by the type of site processing that occurred. Processing along existing or newly created roads was termed "linear processing" and was characterized by wood chipping at regularly spaced intervals along the entire road length of the harvested area. Processing areas generally extended 15–20 m from the edge of the road into the cutblock and had consistent levels of slash throughout the area and regularly spaced chip or sawdust piles (<2 m^3) within 3 m of the road (Figure 12). The second type of processing, termed "focussed processing," was observed less frequently than linear processing. It consisted of processing along the roadside but generally at a single point, usually at a cul-de-sac or turnaround (Figure 13). Focussed processing areas generally had more severe soil disturbance than linear processing areas due to the numerous equipment passes along the block that were required to bring wood to the processing area (Figure 13).

FIGURE 12 *Linear processing site showing the processing area near the road, and residue piles, debris, and connection to the ditchline.*

FIGURE 13 *Focussed processing site showing chip pile storage near the road and connection to the ditchline, and a waste residue pile behind the chip pile (truck provided for scale).*

This project successfully met its three objectives. The results of this study indicate that all tree species used in biomass processing can produce leachate that is toxic to aquatic life under a variety of exposure conditions. Although the field inventory of sites was small (n<20), the results related to hydrologic connectivity, soil compaction, and slash were relatively consistent. To gain a better understanding of regional and provincial practices, the survey should be expanded to other forest districts and regions to increase both sample number and biophysical representation.

There is potential to improve best management practices for biomass processing based on available information. Until recently, the wood biomass industry had been small in British Columbia and elsewhere, so management guidebooks or best management practices were not developed. Because it has been recognized that general forest management guidelines may not be appropriate for forest biomass harvesting and processing operations because sites may be used more intensively than in other operations, which could lead to water quality, habitat, and soil productivity issues (Abbas et al. 2011), best management practices are being developed. In response to the recognized differences between biomass harvesting and general forest harvesting, European nations such as Finland, with its productive biomass energy sector, and many American states have identified areas for improved management of biomass operations specifically with respect to the development of best management practices (Table 5). If biomass harvesting continues to gain prominence in Canada (Paré et al. 2011), then best management practice monitoring similar to that conducted in Europe and the United States should be considered in British Columbia. This study provides a foundation step in that process by presenting a preliminary assessment of potential water quality issues and identifying areas of potential improvement similar to those identified in other jurisdictions, namely:

- disconnecting processing areas, storage piles, and residue piles from ditchlines and streams;
- maintaining natural drainage patterns;
- implementing operational shutdown when soils are susceptible to damage;
- avoiding processing or leaving residue in riparian areas;
- minimizing soil disturbance and compaction, which enhances runoff and erosion; and
- dispersing slash and residue material rather than leaving it as a pile, even for short periods.

Fast roadside residual collection systems can help mitigate leachate generation by limiting chip pile exposure time and improving harvest efficiency, which may be an important economic consideration given the potential rise in future feedstock cost (Lloyd et al. 2014).

TABLE 5 *Best management practice recommendations from European and American jurisdictions, summarized from reviews by Elliot (2010) and Abbas et al. (2011). Additional soil productivity and compaction-specific best management practices are provided in Kabzems et al. (2011).*

Feature	Recommended practice
Processing site	1. Minimize mineral soil exposure. • Minimize turnarounds with equipment. • Use designated skid trails and harvesters with longer booms. 2. Maintain undisturbed buffers along streams. 3. Operate only when soils are dry enough to support equipment without causing compaction or rutting. • Conduct winter logging when ground frost extends at least 15 cm depth. 4. Avoid dragging logs. • Lift ends with skidders and use grapple skidders or forwarders. 5. Minimize on-block traffic. 6. Mitigate skid trails. • Install frequent water bars and cover trails with slash. 7. Use low ground pressure equipment. • Use bigger tires or tracks.
Road network management	1. Locate roads so as to minimize sediment delivery to streams. 2. Install cross drains or ditch relief culverts where there is an adequate buffer between the road and stream. • Consider the fate of road drainage. 3. Install ditch relief culverts 15 m before stream crossings. 4. Close roads when wet, use gravel to build roads, and maintain regularly. 5. Monitor culverts to prevent blockage and diversion. 6. Deactivate roads promptly and remediate crossings. 7. Minimize piling or storage of forest residues in ditches. 8. Minimize disturbance of natural drainage. 9. Keep ditches functional after energy harvest. 10. Leave a continuous vegetation buffer along ditches.
Soil	1. Minimize soil disturbance and removal of the forest floor. 2. Reduce the number of skid trails on a site. 3. Use existing infrastructure and re-establish soil erosion control measures to avoid compaction on closed harvest sites.
Riparian zones	1. Maintain undisturbed buffers. 2. Remove residue/log bridges after use. 3. Remove forest residue from riparian zones and small water bodies after harvesting. 4. Avoid stump removal in riparian buffer strips, streams, lakes, or ditches. 5. Avoid placing clearing debris in riparian buffer strips. 6. Provide breaks in windrows to allow free water movement.

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1 Identification

Assessed by____________________________________

Date________________________

District____________________ Opening ID______________ Block ID____________________

Watershed/Stream____

Watershed Values (Drinking water/ sensitive species)__________________________________

Locate on a 1:10 K Map (GPS location- transfer to shape-file)

i) Block roads
ii) Processing locations and remnant chip piles
iii) Roads and gradient
iv) Stream crossings
v) Riparian zone harvesting and processing locations

2 Leachate Generation Potential

Processing Location ________________________ Pile Dimensions______________________

Chip Size_______________________________ Age of Chips (Condition)________________

Tree Types _____________________________ Wood Storage__________________________

Comments on Leachate Generation Potential:

____

____

____

3 Aquatic Connectivity

Riparian:

Riparian Disturbance Y / N Piles in Riparian Zone Y / N Pile Dimension (m^3)__________

Est. Total Pile Volume (m^3) __________ Coloration of Soil Around Piles ______________

Roadside Work Area:

Road-Side Piles Y / N Pile Dimension (m^3) _______ Est. Total Pile Volume (m^3) _____________

Coloration of Soil Around Piles ____

Channelization Below Piles (Y/N) ___________________

Stream Crossings Downslope of Processing Site (Y/N) _____ Number of Crossings ______________

Slope To Crossings Y / N Est. Road/Ditch Gradient 0–3, 3–5, 5–7, >7

Runoff Diversion/Storage __________________ Ditch/Road Erosion____________________

Soil Pit	Evidence of Compaction	Y ☐	N ☐	
	Photo No. Undisturbed ______		Disturbed ______	
	Unfavourable Substrates i.e. Water Restrict Layer	Y ☐	N ☐	Depth (cm) ________
	Collect Sample for Texture (0–20 cm) No. _______			

Other Soil Disturbance Present (use card) ruts ☐ scalp☐ gouge☐

Explain ____

____

Slash Disposal ☐ 5% ☐ 10% ☐ 25% ☐50% ☐ 75% ☐ 100%

Comments on Delivery Potential:

____

____

____

4 Other Observations (Site observations indicating potential delivery of leachate or other concerns)

____

____

____

____

5 Site Sketch

APPENDIX 2 Summary information for the field inventory

Site	Area (ha)	Time since harvest	Number of processing locations assessed	Total number of processing locations	Sensitive aquatic resource	Processing type	Aquatic connectivity	Soil texture (by hand)	Soil comments	Summary
1	295.8	~6 months	9	9	None	Linear–roadside	Roadside processing; piles 5–16 m^3; connection to collection areas by ditchline	Silty loam	Compaction in processing areas with some ruts; average slash coverage 55%	Consistent low-level soil disturbance concentrated roadside; aquatic connection low due to lack of streams, not practices
2	192.3	<1 year	22	22	Fisheries	Focussed	Both riparian and road–ditchline connection of residue piles to streams	Silty clay	Compaction at all processing areas; rutting, scalping, and gouging in process areas due to high traffic volume; average slash coverage 60%	Large amount of residue volume left on site; some piles >500 m^3; aquatic connection and soil disturbance should be further investigated
3	337.2	<1 year	1	1	None	Focussed–extreme disturbance on landing	No; residue pile directly connected to mainline ditchline, which turns back onto the block	Silty loam	Extreme disturbance on the upper landing: compaction, deep ruts, gouges, and scalping; slash 50%	Main block appears fine but the upper decking area for processing resulted in 100% disturbance in the landing, and soil disturbance, and the operators left a residue pile estimated at >3000 m^3
4	107.1	~6 months	5	5	None	Linear–roadside	No aquatic connectivity due to flat terrain	Sandy loam	Sandy soil; no compaction or other soil disturbance; slash disposal <5%	Small spotty piles along roadside but no significant issues
5	72.7	~3 years	6	6	Fisheries	Linear	No streams in area	Silty clay loam	Compaction in processing area, with some ruts; slash disposal 30–75%	Limited vegetation regrowth in residue areas; no aquatic connectivity
6	230.8	<1 year	1	1	None	Focussed at turnaround	No streams in area	Silty loam	Compaction, minor soil disturbance; average slash cover in operating area ~90%	Large debris pile >10000 m^3 composed of chips, green trees, slash; unlikely to decay or burn. What will be done here?

Continued on the next page

APPENDIX 2 Continued

Site	Area (ha)	Time since harvest	Number of processing locations assessed	Total number of processing locations	Sensitive aquatic resource	Processing type	Aquatic connectivity	Soil texture (by hand)	Soil comments	Summary
7	328.7	~2–3 years	4	4	None	Linear–roadside	None because no channels	Sandy loam	Compaction in processing areas, with some ruts; slash 10%	Winter processing block using old road network; linear processing along roadside; leachate generated by residual piles may reach the roadside but does not enter a receiving environment downstream; road in considerably better shape than many others seen during the fall season; soil disturbance appears to be minimal; winter roads/sites may show lower impact due to snow cover; block is also older and may be recovering
8			3	18				Loam		Continuation of site 7
9		~1 year	4	4	None	Linear–roadside	Appears to be a winter road; surface runoff to the wetland–pond area; no streams elsewhere on the block	Silty clay loam	Compaction at processing site; average slash estimated to be ~19%	
10	93.6	~2–3 years	6	6	Fisheries	Linear–roadside, well-spaced	None; no stream crossings or streams within boundary of block and processing area	Silty clay loam	Compaction and some rutting at processing location; average slash ~65%	No concerns about aquatic connectivity; roadside debris areas are not showing much vegetation regrowth
11	525.6	<1 year	4	Many	None	Linear–roadside	Aquatic connectivity through roadside processing and ditchline as well as from riparian where processing occurred	Silty clay loam	Compaction, some rutting; average slash ~10%	Aquatic connectivity and soil disturbance; appears to be a wet area, which would enhance site issues after felling and processing
12		<1 year	11	11	None	Linear–roadside	Piles in riparian and along roadside; both ditch and riparian connections	Silty loam	Compaction in processing area, some rutting; average slash coverage ~30%	Large chip piles connected by ditchlines to several streams passing through block

Site	Area (ha)	Time since harvest	Number of processing locations assessed	Total number of processing locations	Sensitive aquatic resource	Processing type	Aquatic connectivity	Soil texture (by hand)	Soil comments	Summary
13	No info.		1	1	None	Linear	Yes; riparian processing and connection as well as a road surface covered in a layer of chips that contributes leachate to runoff	Silty clay loam	Severe compaction in work area, channelling leachate to ditch; slash coverage 100%	Aquatic connectivity and soil disturbance; large amount of block road chip piles will deliver leachate; interview licensee
14	16	~6 months	4	On GPS	Fisheries	Linear–roadside	Roadside processing, crossing on block road, which may receive surface runoff; no diversion or storage structure for runoff	Silty clay	Severe compaction in work area, some rutting; slash average 40%	Low aquatic connectivity but disturbance around chip piles
15			1	2	Fisheries	Linear–roadside; one focussed processing location in centre of block	Limited; excellent spacing of cross-drains on steep slope to divert flow back onto block; limited connection at bottom of block; pile connects to ditchline and possibly Saw Creek ~400m away	Silty clay loam	Compaction in processing area with some rutting; average slash ~86%	Aquatic connectivity not an issue; extensive slash coverage in processing area may hamper reforestation
16	No info.	~1 year	3	20	Fisheries	Linear–roadside; one focussed processing location in centre of block	None; stream crossing ~100 m downslope of piles, but ditch diverts flow from crossing	Silty loam	Compaction in processing area; average slash ~75%	Soil disturbance at work area but no aquatic connectivity issues
17	No info.	~1 year	3	23	Fisheries	Linear–roadside	None; no receiving stream; 23 piles average of 171 m^3	Silty loam	Compaction in processing area; slash coverage average 47%	Soil disturbance is focussed roadside; slash coverage may hamper roadside reforestation
18	92.5	~3 years	2	4	Fisheries	Linear–roadside	Processing located at top of slope, connected to a ditchline and channel at base of slope; potential for spring delivery	Silty loam	Minor surface disturbance; slash coverage ~80%	Winter processing location using mainline; linear processing area possibly connected to channel during high runoff, such as spring melt, low risk